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National Institute of Information and Communication Technology

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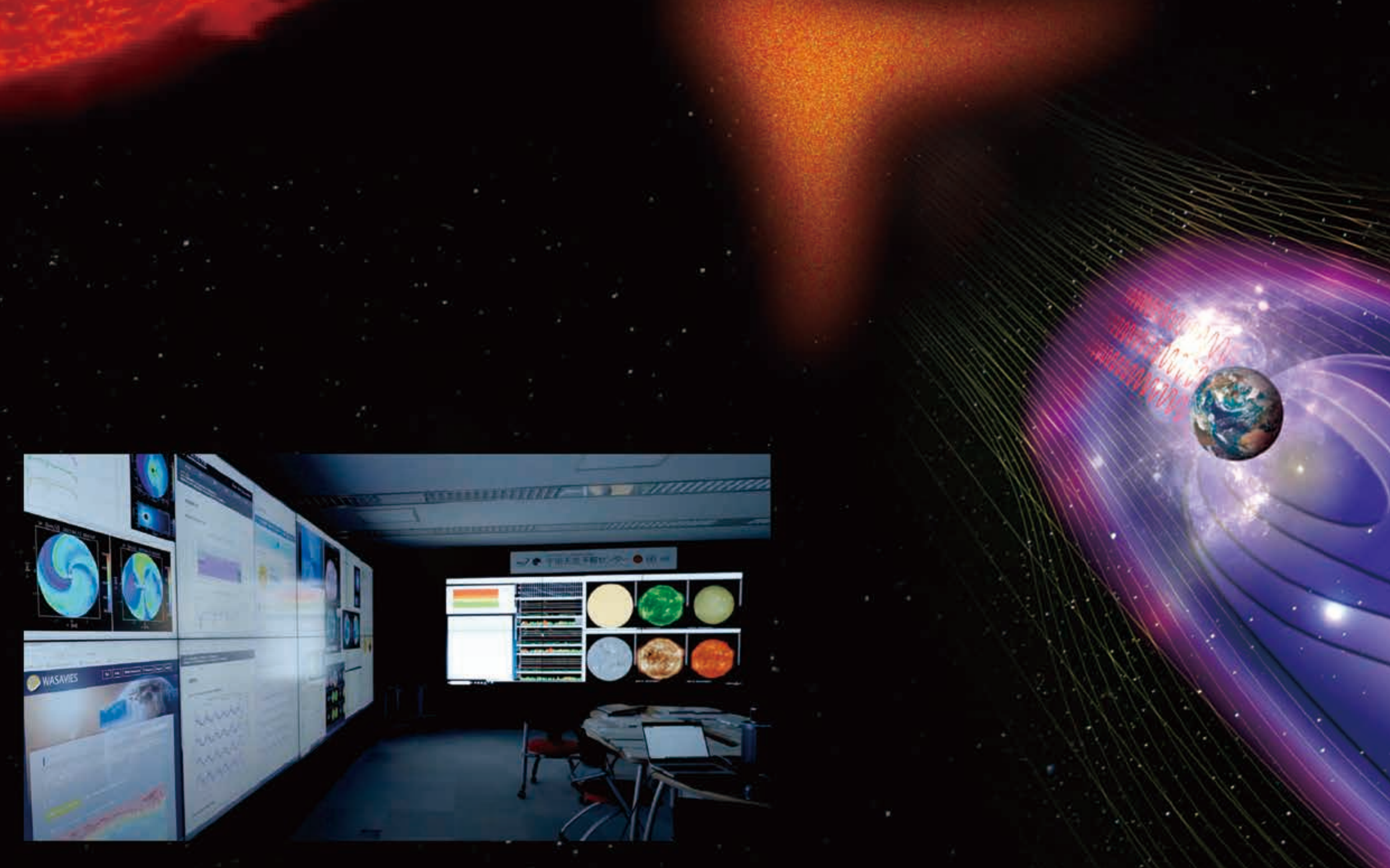
FEATURE

The Sun has reached Solar Maximum! Space Weather Forecast to Protect Social Infrastructure

Interview

The Growing Importance of Space Weather Forecasts for Protecting the Infrastructure of Information Societies



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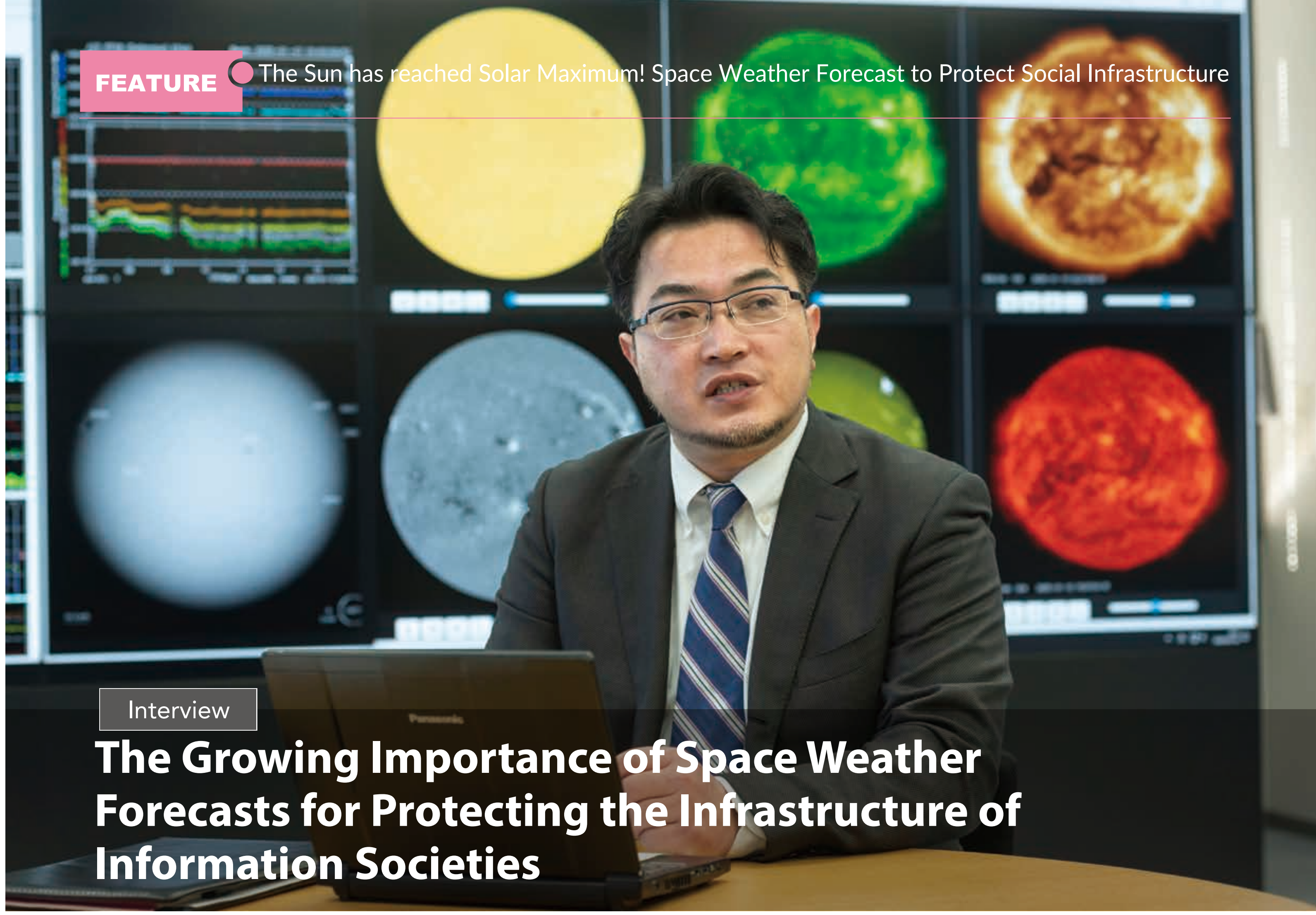
The Sun has reached Solar Maximum! Space Weather Forecast to Protect Social Infrastructure

Cover Photo

A solar flare—the source of space weather phenomena—and the outer space surrounding Earth, which is affected by it. Forecasting takes place every day at NICT's Space Weather Forecast Center (below left).

Photo Upper Left:

On October 11, 2024 Low-latitude aurora observed at NICT's Sarobetsu Radio Observation Facility (Hokkaido)
(Red light in the center, at the bottom of the image)



Interview

The Growing Importance of Space Weather Forecasts for Protecting the Infrastructure of Information Societies

With the Sun at its solar maximum, large solar flares are occurring almost daily on its surface right now. The electromagnetic waves and high-energy charged particles emitted from them have the potential to damage crucial social infrastructure, including satellites and terrestrial communications, broadcasting, and electric power systems. Given modern society's dependence on information and communications via this infrastructure, we cannot afford to disregard the impact that solar flares have on it.

NICT's "Space Weather Forecast" continuously monitors space environment changes, or "space weather" basically originating from this kind of solar activity and produces alerts. We talked to TSUGAWA Takuya, Director of the Space Environment Laboratory, about the recent intensification of solar activity and the latest trends in the space weather forecast, the threats from which are becoming more widely recognized among the general public.

TSUGAWA Takuya
Director of Space Environment Laboratory, Radio Propagation Research Center, Radio Research Institute

After finishing graduate school, he was awarded Japan Society for the Promotion of Science Research Fellowships for Young Scientists for study at Nagoya University and Massachusetts Institute of Technology. He subsequently joined NICT in 2007.
His current work involves space weather forecast-related R&D and services.
Ph.D. (Science).

——What are space weather forecasts and why are they needed right now?

TSUGAWA Solar activity, which is on an 11-year cycle, is expected to reach its maximum in 2025. In fact, it has become more active in the last year or so. When solar activity increases, the scale and frequency of explosive phenomena on the Sun's surface—solar flares increase. The resultant stronger-than-usual emissions of X-rays and other electromagnetic waves, high-energy particles, and masses of electrically charged gas called coronal mass ejections (CMEs) travel to the Earth. These emissions cause disruption in outer space, including in Earth's upper atmosphere, and cause disruptions to various social infrastructure, including satellite operations, HF band and other radio communications and broadcasting, GPS and other satellite positioning systems, electric power grids, and aircraft operations. To ensure the stable operation of such crucial social infrastructure, NICT monitors the status of the Sun and the near-Earth space environment around the clock, 365 days a year, and publishes space weather forecasts that provide information to infrastructure business operators and the public as a whole.

——What specific effects are being seen?

TSUGAWA In May 2024, the aurora borealis, which can usually only be seen in high latitudes, was seen in Japan and attracted much attention, but there were problems with GPS positioning and communications, as well as a decrease in the altitude of low Earth orbit satellites. In 2022, nearly 40 Starlink satellites

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launched by U.S. company SpaceX lost altitude and reentered the atmosphere, causing a loss of function. They had descended from orbit due to atmospheric drag as a result of magnetic storms that cause major disruption to Earth's magnetic field.

Fortunately, there haven't been any failures leading to catastrophe as yet, but if a larger solar flare were to occur in the future, it could have a major impact on society as well. For example, back in 1989, Canada experienced a widespread power outage due to geomagnetically induced current flowing into a terrestrial power grid. And in the 1859 Carrington Event, which is said to be one of the largest solar storms in recorded history, fires are said to have broken out at telegraph stations, which were state-of-the-art infrastructure at the time.

Today, we live in an incomparably more advanced computerized society. The number of satellites for communications and other purposes has increased dramatically over the last few years, and private sector space travel has also been on the rise. If social infrastructure suffered substantial damage, major chaos is expected to occur. As civilization has evolved and humans have expanded into space, the scale of a disaster would become much larger than in the past.

International Collaboration

——How is the international community responding to increasingly active space weather?

TSUGAWA One service already in operation is the use of space weather information at the International Civil Aviation Organization's (ICAO) , which was launched in November 2019. In aviation operations, there are concerns that space weather phenomena may interfere with communications, satellite positioning, and increases in the radiation dose to flight crew. The effects of these are particularly large in the case of passenger aircraft flying through the Arctic region. Using space weather information allows flight routes to be altered and other such steps taken when solar activity is high.

The International Space Environment Service (ISES) is an organization established in cooperation with organizations in charge of space weather to share and provide information on the current status and forecast of space weather. At present, ISES has 21 member countries, with Japan chairing the organization since 2023.

Interest in space weather has also been growing among ASEAN countries in recent years, leading to the formation of the Asia-Oceania Space Weather Alliance (AOSWA), of which NICT has served as the secretariat since 2010.

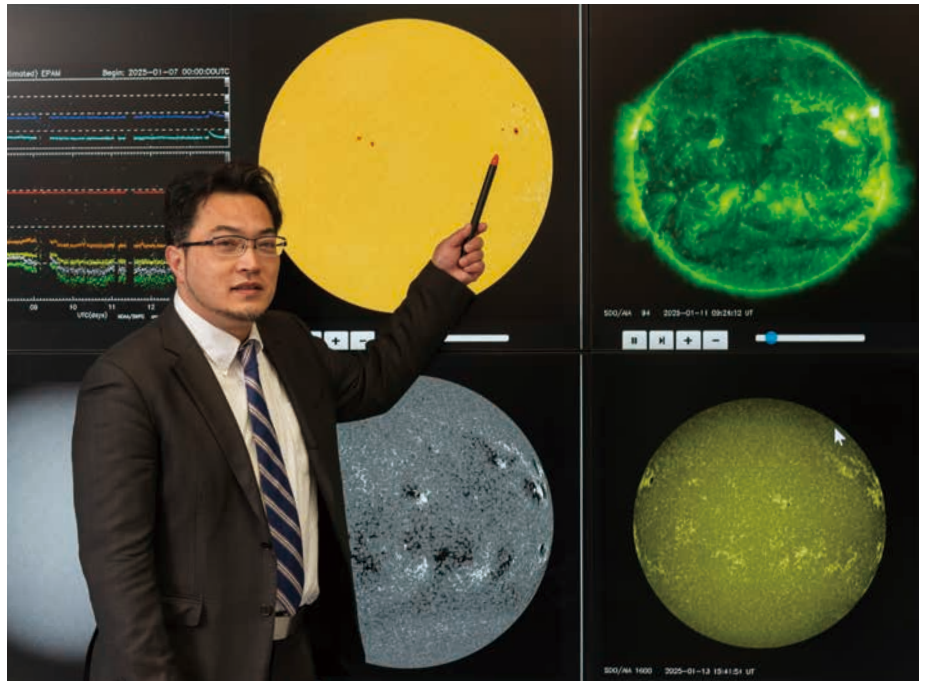
The Scientific and Technical Subcommittee (STSC) of the United Nations Committee on the Peaceful Uses of Outer Space (UN/COPUOS) issued recommendations on space weather services in February 2022, and requested that the Committee on Space Research (COSPAR), ISES, and the World Meteorological Organization (WMO) lead activities relating to space weather. In response to this, representatives of the three bodies gathered at the University of Coimbra in Portugal in September 2023, and formulated the WMO-ISES-COSPAR Coimbra Declaration, which affirms the direction of space weather services and sets out a framework agreement. In November 2023, the first International Space Weather Coordination Forum (ISWCF) meeting was held at WMO headquarters in Geneva, Switzerland. NICT members are also participating in these international initiatives, including as co-chairs, thereby contributing to international space weather activities.

——So would it be fair to say that NICT plays an important role in global space weather forecasting initiatives?

TSUGAWA International cooperation is essential for monitoring a wide range of space environment, from the Sun to the near Earth space environment, including the ionosphere, and Japan is also making a substantial contribution in this area. Japan has been continuously obtaining and providing high-quality data on the ground observation infrastructure necessary for the operation of space weather services for quite a long time. On the other hand, Japan doesn't have the means to implement operational satellite observation from space, so we currently have no option but to rely on data from U.S. and other nations' satellites for the solar and outer space observation data used in Japanese space weather forecasts.

In order to increase the precision of space weather monitoring above Japan, NICT is at present developing sensors for the Himawari-10 satellite set to enter operation in 2029, aiming to fit it with space environment sensors capable of being installed at the same time as its meteorological observation equipment.

Additionally, we're moving forward with research and development focused on forecasting models using rapidly developing AI technologies and technologies to assimilate observation data into numerical models, in order to create more accurate forecasts. On the other hand, it's still difficult for AI to produce precise forecasts of large-scale solar flares, which occur extremely infrequently, so we're striving to increase overall forecasting accuracy and expand the fields subject to alerts by developing solar flare alerts based on physical models at the same time.



——Does the fact that space weather initiatives are being stepped up around the world indicate that there's a need for them?

TSUGAWA Internationally, studies are underway to examine the question of what the actual impact of space weather is likely to be. The United States and the United Kingdom, in particular, have positioned space weather risk and countermeasures as part of their national strategy from an early stage. They regard space weather as a natural disaster that would have a significant impact on society, just like a major earthquake, volcanic eruption, tsunami or similar event. In the situation where various efforts are underway to consider what countermeasures are needed to deal with this situation, close international cooperation is being promoted as international cooperation is necessary.

Trends in Japan

——I understand the Ministry of Internal Affairs and Communications (MIC) organized a study group on space weather.

TSUGAWA Here in Japan, MIC set up the Study Group on the Advancement of Space Weather Forecasting in 2022, which published its report in June that year. The study group drew up worst-case scenarios for Japan that could be triggered by extreme space weather phenomena, and made a range of recommendations about the need for crisis management.

One recommendation was the need for a forecasting and warning system based on new alert levels that take social impacts into account. In space weather forecasts at present, only X-ray strength and other such physical parameters are used as benchmarks in solar flare forecasts and warnings, making it hard for the users who receive this information to understand what kind of impact they will have and how they should respond. The new alert levels set benchmarks that take the social impact into consideration, based on the extent of the impact of each one on social fields, which makes it easier for users to implement response measures when they receive an alert. This is to make them more user-friendly for business operators using the service, in a similar way to hazard projections in weather forecasts.

Collaboration with Private Sector Business Operators and Other Users

——What are your thoughts on collaboration with private sector business operators that use space weather information?

TSUGAWA The use of space is just going to keep on growing with things like the launch of private sector microsatellites and space tourism businesses. Social infrastructure will keep evolving into more advanced forms, too. Under such situations, space weather information is going to become increasingly important.

NICT monitors and predicts space weather, which is extremely important for modern society, and is building a robust system to properly provide space weather information and to reliably issue space weather forecasts without interruption.

On the other hand, as social systems become increasingly diverse, it seems likely that there will be aspects of individual social systems that NICT won't be able to fully address singlehandedly. We would like to collaborate with private sector business operators to realize detailed services for individual systems using NICT's observation and forecast information.

Maintaining close dialogue with private sector business operators and other users in order to tap into changing needs and new ideas is crucial to ensuring that users can actually utilize this information. We intend to engage in ongoing discussions with users through such platforms as NICT's Space Weather Users Forum and Space Weather Users Council. It will also be important to develop human resources with a deep understanding of space weather information.. Among the ideas that emerged from MIC's study group has been the creation of systems for spreading knowledge, such as the development of space weather forecasters, so we want to discuss these ideas further at meetings of the Users Council and the like.

NICT is committed to further promoting space weather forecasting and contributing to the stable operation of a strong and robust social infrastructure that is resilient to failures.

Space Weather Forecasting Service

KUBO Yûki

Associate Director of Space Environment Laboratory, Radio Propagation Research Center, Radio Research Institute

Dr. KUBO joined Communications Research Laboratory (current NICT) in 1998. after receiving a degree of MSc in astronomy. He has worked for a research on space weather forecasting such as a solar radio observation and cosmic rays, and has also managed space weather forecast operation.
Ph.D.

Imagine what could happen if large solar flares were to occur. They would likely raise concerns about the potential impact on Earth and its social infrastructure. Space weather forecasting*1 is conducted to address these concerns. Given that the sun has reached its solar maximum, public interest in the potential impact of solar flares and other solar activities has grown significantly. Space weather forecasting continues to evolve to mitigate the effects of solar activity on social infrastructure, thereby contributing to human well-being and social stability.

Introduction

An intense emergency response takes place whenever the staff of the Space Environment Laboratory (SPE) receives a report from space weather forecasters that an X-class flare*2 has occurred. SPE members urgently analyze relevant data to estimate the impact of the solar activity on Earth. If their analysis finds that there will be no significant impact on Earth, they breathe a sigh of relief.

However, when large flares were detected in May and October 2024, these analyses found that significant impacts on Earth were possible. Accordingly, the SPE members decided to issue alerts by posting announcements on the National Institute of Information and Communications Technology (NICT) website and holding press conferences. Consequently, many media outlets reported on the potential impact of solar activity on social infrastructure.

Space weather Forecasting and Information Delivery

NICT is Japan's only public institution that carries out space weather forecasting as a legally mandated service. NICT's predecessor, the Radio Research Laboratory (part of the former Ministry of Posts and Telecommunications), began providing the earlier version of this service—the radio wave propagation alert—in the early 1950s. The purpose of this service was to detect early signs of potential shortwave communication disruptions and make this information available to users. In 1988, the service was given its current name: "space weather forecasting." The core function of this service is continuous, year-round monitoring and analysis of solar activity and the space environment around Earth. NICT conducts its own observations and simulations of the sun, solar wind and Earth's magnetosphere and ionosphere (Figures 1 and 2). In addition, it collects and analyzes observational data and other relevant information from domestic and international organizations, providing various types of space weather-related information around the clock.

The aviation industry is the primary user of space weather information for operational purposes. In recent years, space weather information was added to Annex 3 of the Convention on International Civil Aviation by the International Civil Aviation Organization (ICAO), a specialized agency of the United Nations. In response, on November 7, 2019, the four ICAO space weather centers—operated by the United States, the European Union, the Australia-Canada-France-Japan (ACFJ) consortium and the China-Russia consortium—began providing space weather information relevant to commercial aircraft navigation. NICT has been actively involved in the operations of the ACFJ consortium.

As of 2025, NICT's space weather forecasting service has three major functions. First, when space weather phenomena exceed predetermined thresholds, NICT promptly and automatically issues the relevant information. Second, in the event of intense or significant phenomena, it issues emergency notifications—including information confirmed by space weather forecasters—at any time of the day or night. Third, NICT provides space weather forecast updates twice daily, incorporating assessments made by NICT researchers and space weather forecasters. These updates are distributed via email and the NICT website to various industries, including aviation, communications, broadcasting, satellite positioning, satellite operations, electric power and the media. In addition to these services, NICT annually hosts the Space Weather Users Forum and the Space Weather Users Council to promote the use of space weather information and facilitate discussions with users. The goal is to enhance the quality and accessibility of NICT's space weather forecasting service.

*1 A trademark registration application for the term "Space Weather Forecasting" was submitted to the Japan Patent Office by the Radio Research Laboratory — part of the former Ministry of Posts and Telecommunications — on June 9, 1988. Registration was granted on November 29, 1991.

*2 The intensity of solar flares is categorized into five classes: A, B, C, M and X, in order from lowest to highest. Therefore, X-class solar flares are the most intense.

*3 https://www.soumu.go.jp/main_sosiki/joho_tsusin/eng/pressrelease/2021/12/20_02.html

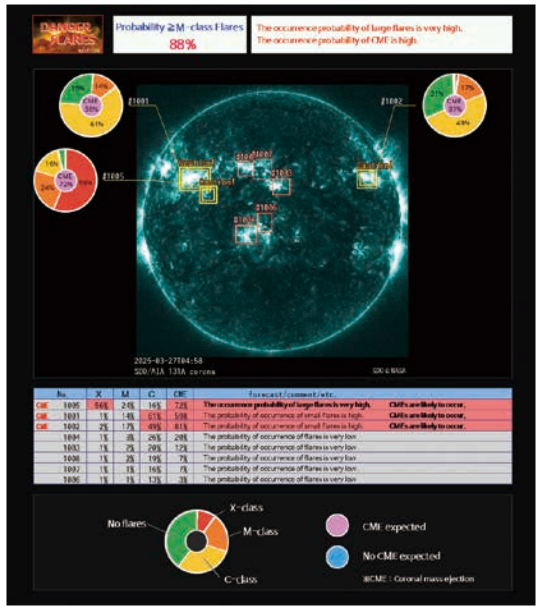


Figure 1 DeFN is an AI-based system being developed to predict the probability of solar flares occurring in each of four intensity classes.

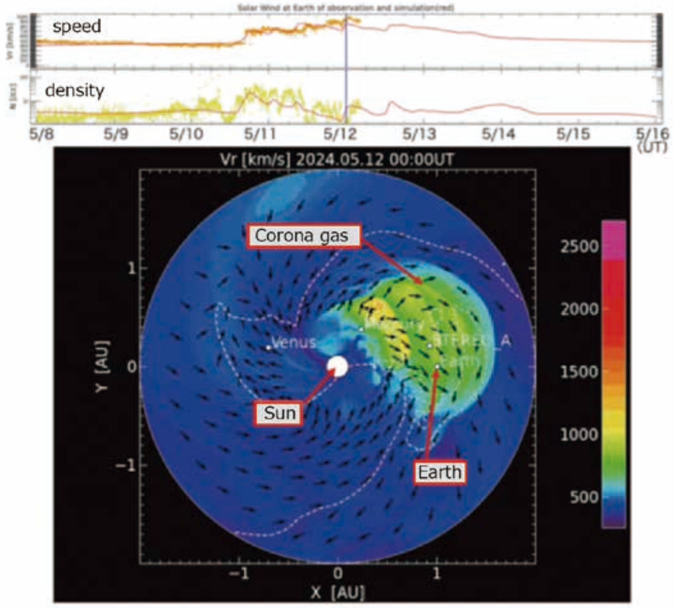
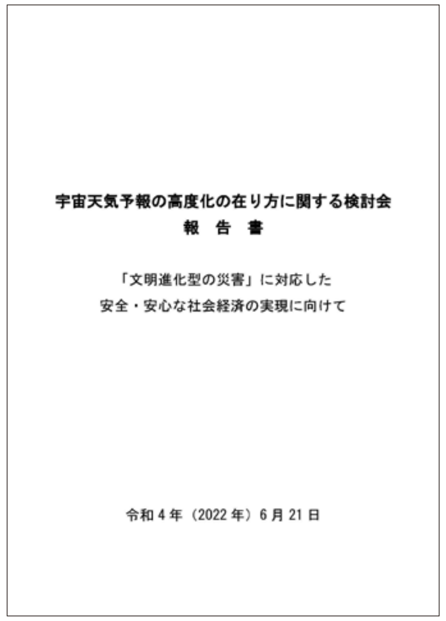


Figure 2 SUSANOO is a numerical simulation model used to forecast the arrival of coronal mass ejections at Earth.

Study Group on the Advancement of Space Weather Forecasting Meetings

In December 2021, the Ministry of Internal Affairs and Communications (MIC)—which oversees NICT's space weather forecasting service—convened a series of meetings of the Study Group on the Advancement of Space Weather Forecasting*3 to discuss the future direction of the service. The meetings brought together a wide range of participants, including space weather experts from NICT, universities and other research institutions; industries that rely on space weather forecasting (e.g., communications, broadcasting, satellite positioning, electric power, aviation, satellite operations and insurance); and relevant public sector organizations (e.g., MIC, the Ministry of Education, Culture, Sports, Science and Technology, the Ministry of Economy, Trade and Industry, the Ministry of Land, Infrastructure, Transport and Tourism, the Ministry of Defense, the Japan Meteorological Agency and the Cabinet Office). This six-month series of meetings was the first of its kind in Japan. The final report was published on June 21, 2022 (Figure 3). The meetings and the report demonstrate Japan's national commitment to the advancement of space weather forecasting and mark a significant milestone in the country's progress in this field.

A key agenda item thoroughly discussed during the meetings was improving the clarity of alerts. To achieve this, several working groups (WGs) were formed, bringing together representatives from industry, academia, the public sector, researchers and users of space weather forecasting. These groups collaborated to establish new alert issuance criteria while considering the social impacts. As a result, new alert issuance criteria were developed for three sectors: certain fields of communications and broadcasting, satellite operations and aircraft exposure. Systems necessary to issue alerts in these sectors are currently under development, and revised space weather alerts are expected to be available to inform the general public in the near future. In addition to these three sectors, new alert issuance criteria are being developed for other sectors, such as satellite positioning and electric power. This ongoing effort involves continued collaboration between the WGs, relevant industries and other stakeholders.



宇宙天気予報の高度化の在り方に関する検討会
報　告　書

「文明進化型の災害」に対応した
安全・安心な社会経済の実現に向けて

令和４年（2022年）６月21日

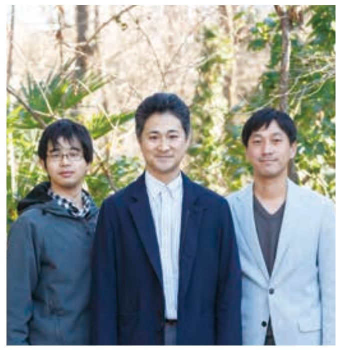
Figure 3 Report produced based on discussions held by the Study Group on the Advancement of Space Weather Forecasting. (in Japanese)

Conclusion

In response to the sun reaching its solar maximum, public interest in the potential impact of solar activity on social infrastructure—particularly in industries such as aviation, communications and broadcasting, satellite positioning, satellite operations, electric power and insurance—has grown significantly. I have seen both a growing number of requests for space weather forecasting and rising expectations for our forecasts. To meet these demands, NICT has been improving its space weather forecasting services—including the development of new alert issuance criteria and systems—while continuing to provide space weather information.

Development of Radiation Monitors for Space Weather (RMS) for the Next Meteorological Satellite "Himawari-10"

SAITO Shinji
Senior Researcher, Space Environment Laboratory, Radio Propagation Research Center, Radio Research Institute
After completing graduate school, worked at Los Alamos National Laboratory in the United States and at the Institute for Space and Earth Environment, Nagoya University before joining NICT in 2019. Engaged in earth radiation belt modeling and development of Radiation Monitors for Space weather (RMS). Ph.D. (Engineering).



From left, Dr. NAMEKAWA, Dr.OTSUJI and Mr. Park,
Space Enviromnet Laboratory,
Radio Propagation Research Center,
Radio Research Institute

NAMEKAWA Taku
Researcher

OTSUJI Kenichi
Researcher

Park Inchun
Researcher

Space is an ever-changing environment filled with flurries of high-energy protons and electrons. These particles can pose a risk to space exploration and use after being emitted from the Sun or becoming trapped in Earth's magnetic field, as they can cause degradation or defects in spacecraft[*1]. We are developing Radiation Monitors for Space weather (RMS) that will be fitted to the next meteorological satellite "Himawari-10," in order to monitor the space environment.

The Space Environment Surrounding Earth

Rather than being an empty vacuum, space is an ever-changing environment filled with flurries of high-energy protons and electrons, which originate from the Sun. When solar flares—explosive phenomena on the Sun's surface—occur, the number of highly energetic protons released can increase a thousandfold or more compared with the normal level, and magnetic storms can result when gases around the Sun are blown into space by solar flares and collide with the Earth magnetosphere, which is the dominant magnetic field surrounding our planet. In the Earth magnetosphere is a region called the Van Allen Belts, in which high-energy electrons are trapped; when a magnetic storm occurs, the quantity of these electrons can fluctuate sharply. In near-geosynchronous orbits, the quantity of high-energy electrons can increase a thousandfold or more in a single day. Thus, the space environment surrounding Earth changes in very dynamic ways due to the Sun's influence.

Space Environment Risks Relating to Space Exploration and Use

The space environment is a factor in spacecraft defects and degradation. High-energy protons—which increase in number as a result of solar flares—act on the elements in semiconductors used in spacecraft, flipping the logic bits, which can be a factor contributing to system malfunctions. High-energy electrons build up on the surface of and inside insulating material used in spacecraft, causing the material to become charged. Once the electric charge exceeds a certain level, discharging it can cause material failure or electromagnetic radiation, which leads to spacecraft defects. The deterioration in the space environment resulting from increases in high-energy protons and electrons poses a risk to the safe, secure exploration and use of space, not only for the satellites that provide the communications and positional information services that we now use every day, but also to the spacecraft and astronauts that will develop the surface of the Moon in the future.

Features of RMS

We are developing a proto flight model of RMS to be fitted to the next meteorological satellite "Himawari-10," in order to monitor the risks to spacecraft arising from the space environment. This device has three components: an electron radiation monitor (RMS-e), a proton radiation monitor (RMS-p), and a data processing unit (RMS-dpu) that will link them to "Himawari-10." The RMS-e (Figure 1) measures electrons in Van Allen Belts, which have a wide-ranging distribution, from a few dozen kiloelectron volts (keV)[*2] to several megaelectron volts (MeV). The device has two detectors made from a laminate consisting of several layers of silicon semiconductors: one for detecting electrons on the low energy side (50 keV–1300 keV) and one for detecting electrons on the high energy side (0.8 MeV–5 MeV). Each is capable of high-precision measurement. The RMS-p (Figure 2) is also divided into detectors for measuring low-energy and high-energy protons; as in the RMS-e, the low energy side measuring device uses a laminated silicon semiconductor detector, which detects the number of protons injected and their energy (10 MeV–500 MeV). However, the interior of the high energy side detector is fitted with silica glass, which enables protons in the range 350 MeV–1 GeV or so to be observed by detecting Cherenkov light[*3] produced when the high-energy protons pass through it. We have ensured that these measuring devices can be efficiently linked via the RMS-dpu (Figure 3) by connecting them to the satellite bus system of "Himawari-10".

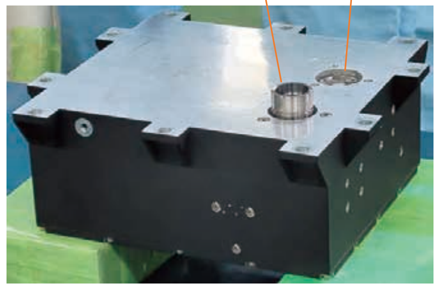


Figure 1 Exterior of the electron radiation monitor (RMS-e) engineering model

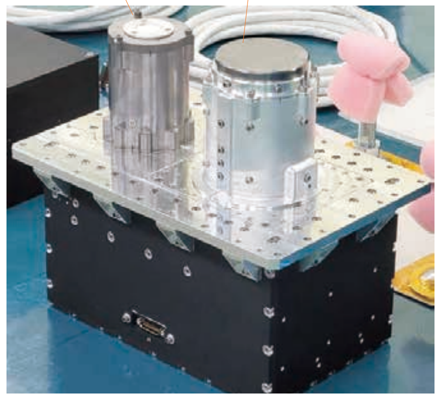


Figure 2 Exterior of the proton sensor (RMS-p) engineering model

Figure 3 Exterior of the data processing unit (RMS-dpu) engineering model

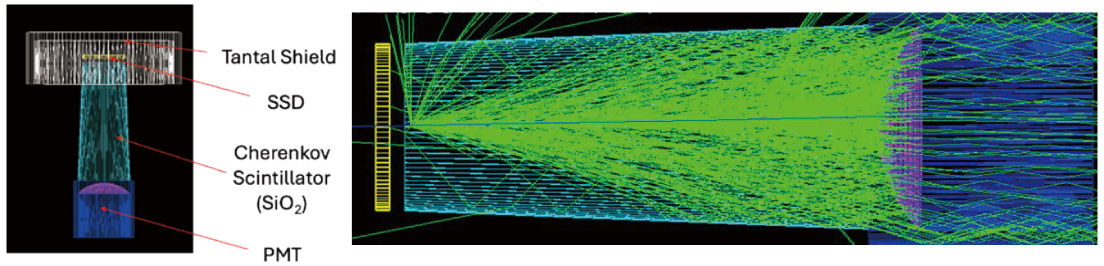


Figure 4 Results of analysis of the trajectory of high-energy protons within silica glass (SiO2) installed in the RMS-p

Calibration of RMS

Calibration is used to determine how the silicon semiconductor detector and silica glass react to the high-energy particles. They are subjected to irradiation tests in which they are irradiated with particle beams that have a known energy level, and the relationship to the output is observed for the purpose of calibration. By means of simulations in which the trajectories of particles in a substance are calculated, we calculate what kind of reactions the high-energy particles injected from outside the measuring device cause in the silicon semiconductor detector and silica glass, and how their trajectories change as a result (Figure 4). We can achieve even more precise calibration by comparing the results of the simulations with those of the irradiation tests, and referring to the results of simulations under conditions that cannot be achieved in irradiation tests. And once the satellite has actually been launched, we will also ensure that accurate measurement of the space environment can be carried out by performing cross calibration using data obtained from space environment sensors fitted to other satellites.

Future Prospects

NICT distributes space weather information by gathering and analyzing space weather data from various Japanese and international organizations around the clock. However, at present, we are reliant on Western observations for most of the data obtained from measuring the space environment, and it can be difficult to gain a precise understanding of the situation in the space environment above Japan, due to differences in local time. In particular, the environment in the Van Allen Belts, which have geosynchronous orbits, differs substantially according to local time, so in situ measurement is essential in order to understand the space environment above Japan. At NICT, we plan to fit RMS to the next meteorological satellite "Himawari-10" and start monitoring the space environment in a geosynchronous orbit over Japan from 2029. In addition, by undertaking international collaboration for the purpose of cross calibration with other satellites, and comparing and verifying the data obtained by various countries, we aim to gain a global understanding of the space environment and to increase the precision of space weather forecasting. While pursuing these international initiatives, we will further the development of RMS in order to carry out space weather forecasting that contributes to the safe, reliable exploration and use of space to support social infrastructure.

＊1 Vehicle launched by a rocket or the like and used in outer space.
＊2 An electron volt (eV) is the average energy of an electron with a temperature of around 10,000 K.
＊3 The light produced when a charged particle passes through a substance faster than the speed of light.

Space Weather in the Thermosphere and Ionosphere

JIN Hidekatsu

Senior Researcher,
Space Environment Laboratory,
Radio Propagation Research Center,
Radio Research Institute

After completing a doctoral course, joined NICT in 2004. Engaged in research on space weather in the upper atmosphere (thermosphere and ionosphere). Ph.D. (Science).

Recent years have seen our society's use of space shift up a gear. Examples include the advancement of internet communications networks into space with the launch of satellite constellations made up of numerous small satellites, and the routine use on smartphones of positional information obtained from global navigation satellites. The thermosphere and ionosphere in the Earth's upper atmosphere are where satellite constellations are being constructed, and this region is also a medium that affects global navigation satellite radio waves. As solar activity approaches its maximum, there have been reports that turbulence in the thermosphere and ionosphere had impacts on space infrastructure. NICT is working to develop more advanced technologies to monitor and forecast such phenomena.

The Thermosphere and Ionosphere: The Front Line of the Accelerating Use of Space

The thermosphere is the uppermost part of Earth's atmosphere (at an altitude of around 90–600 km); within this layer is the ionosphere, which is formed as a result of the Sun's ultraviolet rays decomposing atoms and molecules into ions and electrons. This region is regarded as the boundary between Earth's atmosphere and outer space. Various phenomena are induced in it by the effects of solar radiation and the magnetospheric inputs from above, and the impact of meteorological weather phenomena reaching it from below (Figure 1). At the same time, because the sphere of our society's activities now extends as far as the thermosphere and ionosphere, natural phenomena occurring in this region can pose a threat to our use of space. The air in the thermosphere acts on satellites and space debris in the form of atmospheric drag, which affects their orbit and attitude. In particular, recent trends in building satellite constellations over the last few years have caused a surge in the number of satellites in orbits close to Earth (low Earth orbits), so these effects are increasingly important. Additionally, as electrons in the ionosphere vibrate in response to radio waves, they affect radio waves on a wide range of frequencies, including high frequency waves (HF; 3–30 MHz) used for marine and aeronautical radio communications, and the 1–2 GHz band used by global navigation satellite systems (GNSS). Accordingly, the state of the ionosphere can alter communications and GNSS performance. The use of GNSS has recently become particularly prevalent in smartphones, drones, and autopilot systems, making the ionosphere increasingly important in the positioning field.

Impact of Large-scale Space Weather Phenomena in Recent Years

With solar activity having been approaching its maximum over the last few years, there have been reports that turbulence in the thermosphere and ionosphere is impacting the use of space. In May 2024, massive plasma clouds ejected from the Sun during solar flares reached Earth, causing the largest geomagnetic disturbance (magnetic storm) in 19 years. This attracted significant attention in the news and on social media, due to the auroras it caused across large parts of Japan. At the same time, auroral activation means that powerful electric currents flow from the magnetosphere to the thermosphere and ionosphere. These currents heat the air in the thermosphere and disrupt the electron density distribution in the ionosphere via electrical forces. Significant deviations of electron density from the normal state (ionospheric storms) generated in this process were particularly prominent in the May 2024 event. Smaller scale irregularities of electron density distribution were also observed flowing through the atmosphere over Japan (Figure 2).

According to the Geospatial Information Authority of Japan (GSI), there is a possibility that GNSS positioning was affected during the time period when these ionospheric disturbances were occurring, and that there was an increase in the margin of error not only in the single-frequency positioning method used in car navigation systems and smartphones, but also in the dual-frequency method used in measurement and the like, which is not readily affected by the ionosphere (https://www.gsi.go.jp/denshi/denshi45043.html; https://www.gsi.go.jp/denshi/denshi45044.html).

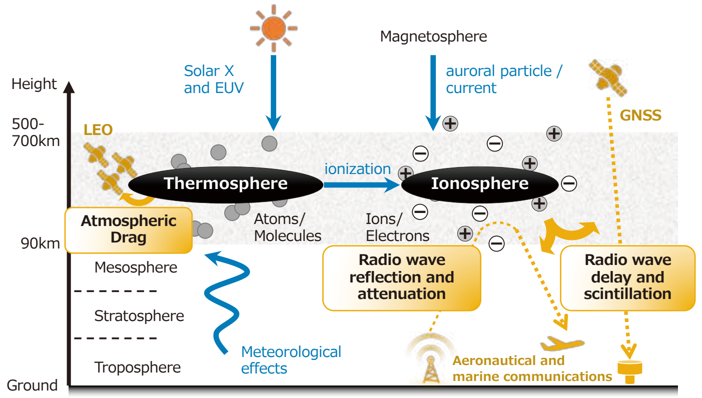


Figure 1 Schematic of the thermosphere and ionosphere

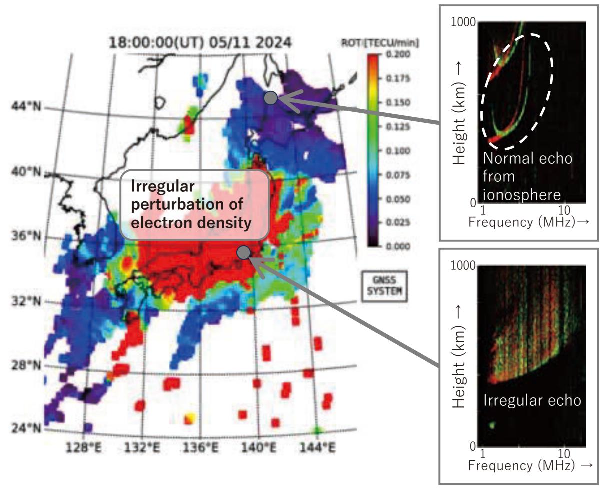


Figure 2 Observation of the ionosphere during the May 2024 magnetic storm (Left: TEC fluctuation rate; Right: Ionosonde observations)

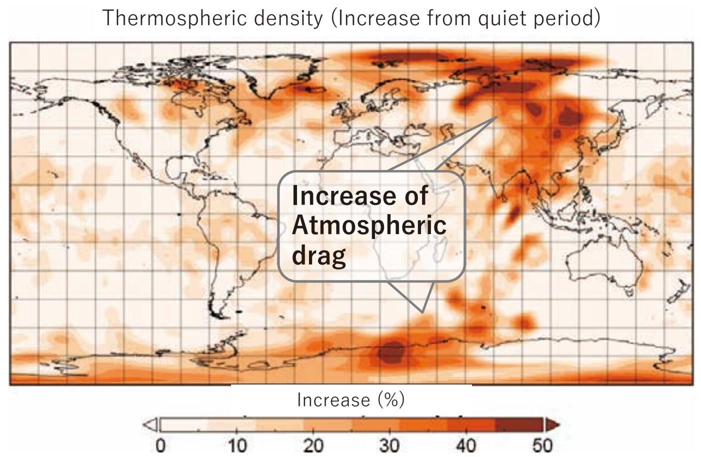


Figure 3 Results of real-time simulation of the thermosphere during the February 2022 magnetic storm

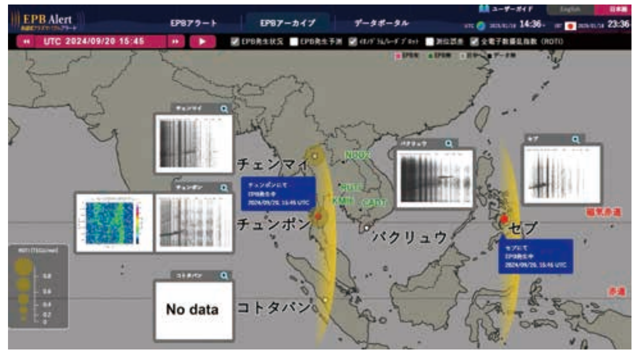


Figure 4 Plasma Bubble Alert System (https://epb-alert.nict.go.jp/en/index.html)

Low Earth orbit satellites were reportedly affected by air turbulence in the thermosphere during magnetic storms in February 2022. The magnetic storms on that occasion were moderate in scale, of a kind that occurs around once a month on average, but a few dozen satellites that had been launched as part of a satellite constellation plunged from the thermosphere into a lower level of the atmosphere and were lost. Increased atmospheric drag on the satellites was reported to be the cause of this event. It is thought that this caused the satellites to slow down and lose centrifugal force, resulting in them falling from orbit. Based on the real-time simulation described below, we have confirmed that the auroral current system heated the air in the thermosphere, causing the dense atmosphere at a lower altitude to expand to higher altitudes and spread, which led to an increase in atmospheric drag (Figure 3).

Approaches to Monitoring and Forecasting the Thermosphere and Ionosphere

To mitigate the risks posed by such thermospheric and ionospheric phenomena to the use of space, NICT is working to develop more advanced techniques to monitor and forecast them. In terms of ionospheric monitoring, we carry out observations at four locations in Japan and in the Antarctic using observation equipment called ionosondes, which measure the vertical structure of electron density. We also derive the total electron content (height integrated electron density) based on data from GSI's GNSS receiver network (see Figure 2 for an example of observation). In addition, with the cooperation of local organizations in Southeast Asia, we have deployed an observation network of ionosondes and other observation equipment to monitor ionospheric disturbances called plasma bubbles, which originate in the equatorial region, grow, and spread to low-latitude regions, including the southern part of Japan. We are also introducing machine learning techniques to extract ionospheric features from the observation data. In Southeast Asia, we have built the Plasma Bubble Alert System, which detects the formation of plasma bubbles in real time; this system became open to public in December 2024 (Figure 4).

Meanwhile, with regard to approaches to forecasting ionosphere and thermosphere, we have developed a whole atmosphere and ionosphere model called GAIA (https://gaia-web.nict.go.jp/index_e.html) in cooperation with Kyushu University and Seikei University, and are working to make it even more advanced. So far, we have carried out real-time calculations by using the latest data with GAIA at the time of calculation (see Figure 3 for an example of calculation results). The results of these calculations are also used in the HF-START web tool (https://hfstart.nict.go.jp/index.html), which visualizes radio wave propagation. In addition, we are moving forward with the installation of a data assimilation technique that will reduce the margin of error in models with the aid of ionospheric observation data, in order to improve forecast accuracy. We plan to begin real-time and forecast calculations using the data assimilation technique by the end of FY2025.

Promoting the Social Implementation of Space Weather Forecasting

Encouraging private sector use and commercialization

NISHIZUKA Naoto

Senior Researcher,
Space Environment Laboratory,
Radio Propagation Research Center,
Radio Research Institute

After completing graduate school, Dr. NISHIZUKA worked at JAXA, NAOJ, and UCL/MSSL. He joined NICT in 2014. He has engaged in R&D of solar flare prediction models using machine learning. He also promotes its social implementation. Ph.D. (Science).

With the use of satellite communications and GNSS-based satellite positioning, space has become a familiar part of everyday life for us. At the same time, as solar activity intensifies, the economic impacts of the space environment are also growing, including the loss of 40 low Earth orbit communications satellites due to a magnetic storm. Space weather forecasting protects social infrastructure by mitigating these risks. While undertaking the social implementation of space weather forecasting, NICT aims to bolster linkages to social infrastructure, in an effort to encourage private sector use and commercialization.

Background

The space industry has often been in the news in recent years, due to such developments as the use of satellite constellations and the start of private sector space travel. At the same time, space security issues have also come under the spotlight, including the resilience of space infrastructure and the problem of space debris. There are even ongoing deliberations concerning business activity involving the Moon's surface. The 2022 loss of 40 Starlink satellites due to a magnetic storm had a major impact. Under the long-term strategy mapped out in the U.S. National Space Strategy, NOAA, NASA, the Air Force and Space Force, universities, and space-related startups are working together on efforts to distribute more user-friendly space weather information and to create private sector businesses.

In Japan, too, in addition to existing large corporations in the space sector, numerous space startups have been launched, and companies are also moving into the space business from other fields. Amid this situation, satellite launches and space-related services are thriving, so the use of space weather information is also growing in importance (Figure 1). The commercialization of space weather forecasting is a key topic in NICT's current Medium-to-Long-term Plan, with in-depth discussions taking place in such forums as the Space Weather Users Council and the Ministry of Internal Affairs and Communications' Study Group on the Advancement of Space Weather Forecasting.

Encouraging the Private Sector Use and Associated Challenges

Encouraging private sector use is also the next challenge for NICT in regard to our space weather forecasts. While monitoring the effects of solar activity on short wave communications is the starting point for the composition of space weather forecasts, we have recently begun to include impacts on businesses in other fields in our forecasts. Effects differ according to each country's latitude and industries, but the economic impacts are presumed to be greatest in the five fields of communications and broadcasting, satellite operation, aviation, satellite positioning, and electric power. Consideration is also given to the perspectives of deep space exploration, and national defense and disaster prevention (Figure 2).

The key difficulty involved in the social implementation of space weather forecasting is turning the results of basic research by researchers into an operational form that can be distributed to business operators as user-friendly information. Although space environment data is shared via international cooperation, we cannot ascertain the extent of impacts on social infrastructure systems unless we ask individual companies. Response measures also differ from one system to another, and there is a need for easily comprehensible wording that avoids the use of technical terms, too. At NICT, we are conducting surveys of impacts on individual companies, while also undertaking needs-based research and development, formulating new alert standards, and preparing usage guidelines.

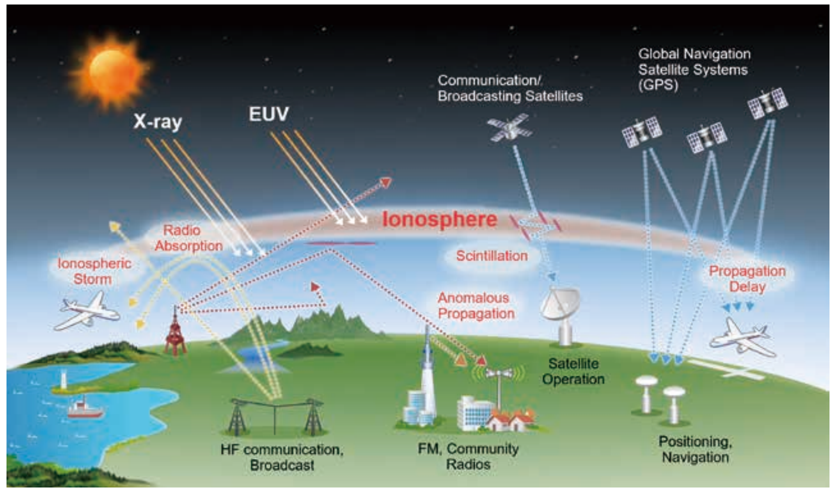


Figure 1 Social impacts of space weather (solar flares)

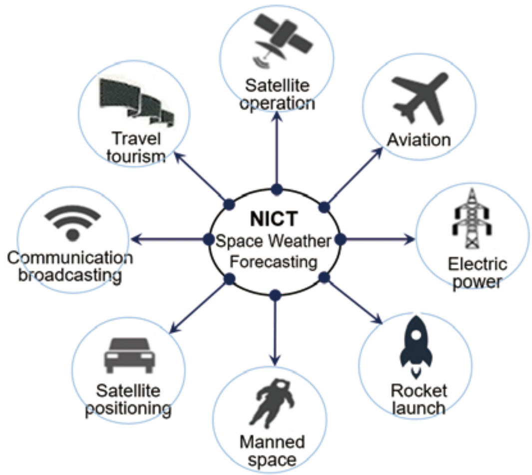


Figure 2 Fields in which space weather forecasts are used

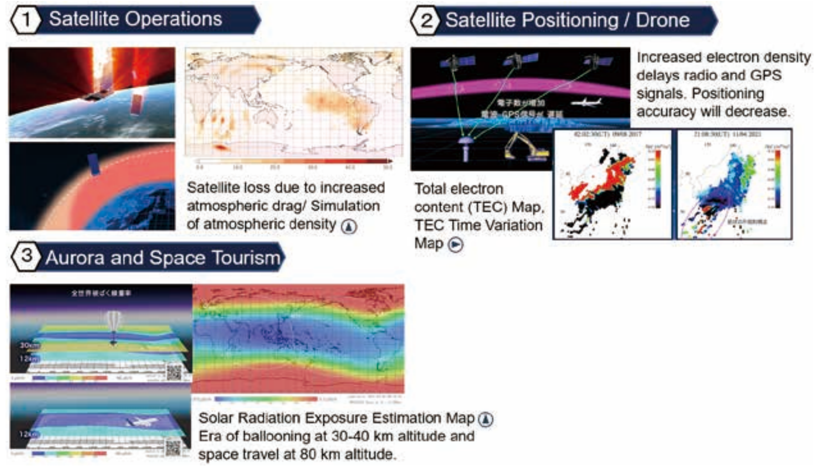


Figure 3 Three fields in which we conducted a survey of market needs and associated space weather forecasting solutions

Survey of Market Needs for Space Weather Forecasts

Since the previous fiscal year, NICT has been undertaking market research aimed at commercialization, and empirical research focused on the production of a concept video. As part of this research, we gathered information from not only the Space Weather Users Council, but also companies participating in CEATEC, Nihonbashi Space Week, the Space Weather Workshop held in the U.S., and NICT Open House. In addition, as the U.S. and Australian embassies are engaged in space startup matching, we took advantage of this opportunity to conduct a survey to gather information from overseas companies as well, and ultimately obtained responses from more than 80 space-related companies.

In terms of fields, the companies can be categorized into the following: satellite-related companies, insurance companies, trading companies, human spaceflight, lunar surface exploration, server-operating companies, travel companies, rocket-launching companies, airlines, GPS usage companies, communications and broadcasting companies, and new business services companies. Although few companies want to pay money to use space weather forecast information at this stage, we were able to ascertain the issues faced by each company and identify latent needs relating to space weather. Many respondents expressed a wish for a space weather data API, and we learned that in Japan, too, an increasing number of companies are interested in the commercialization of space weather services.

Solution of Problem by Space Weather Forecasting and the Concept Video

The research and development that we conduct at NICT takes a multidisciplinary approach to the Sun, interplanetary space, the magnetosphere, and the ionosphere, and covers a diverse array of topics, including ground-based and satellite observation, numerical modeling, and AI technologies. Based on research into the ionosphere and magnetosphere, which directly affect radio wave propagation and satellite operation, we have released a shortwave propagation simulator, along with satellite charging and solar radiation exposure prediction apps. In addition to conducting real-time simulation of effects on low Earth orbit satellite operation with the aid of a model of Earth's atmosphere, we have engaged in forecasting operations for solar flares using AI technology, and have put out a call for companies to license our patent (Figure 3).

Based on the results of our market research, we have also produced a concept video focused on fields with high needs for space weather forecasting (Figure 4). Highlighting the fields of satellite operation, satellite positioning and drones, and tourism and space travel, the video takes as its starting point the challenges and issues faced in each field, and explains in specific terms how space weather forecasting solutions can resolve those problems. While introducing in specific terms who can benefit from the data and information provided by NICT, the video has a composition that makes it easy to form an impression of the nature of these businesses, so we hope operators of relevant businesses will watch it.

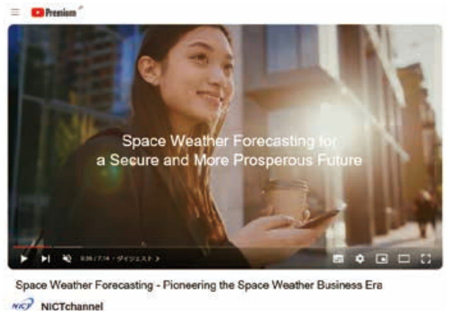


Figure 4 Space Weather Forecast Concept Video (https://www.youtube.com/watch?v=3t-vlX2HcqQ (narrations in Japanese))

Future Prospects

Space weather startups have begun to emerge in recent years, primarily overseas, and efforts to encourage the private sector use of space weather information are progressing. In Japan, too, the nation's first space weather startup has been established, in the form of the Space Weather Company, and efforts to commercialize space weather forecasts are gaining momentum through cooperation between NICT and private sector companies. With a primary focus on fields identified by our market research as having high needs, we are working on research and development for a space weather information sharing platform, and are also considering a space weather forecaster system to ensure that space weather forecasts are used appropriately. We hope you will continue to keep an eye on NICT's space weather forecasts.

The Charging and Discharging of Spacecraft Caused by the Space Environment

ENOKI Kaisei

Researcher (Tenure-Track), Space Environment Laboratory, Radio Propagation Research Center, Radio Research Institute,

After completing graduate school, he joined NICT in 2024. He is engaged in research on the charging and discharging of spacecraft caused by the space environment. Ph.D. (Engineering).

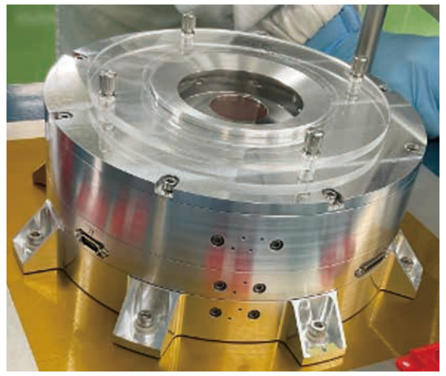


Figure 1 Engineering model of an on-board charge measurement device for spacecraft

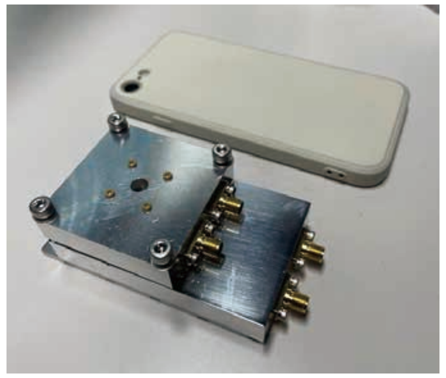


Figure 2 The small charge measurement device currently under development

We have reached an age in which satellites and other space infrastructure support a variety of information and services essential to daily life, including the weather information and location information we obtain from our smartphones. As the years to come bring an increase in self-driving vehicles and the use of drones to transport supplies, among other services, space infrastructure is set to become an indispensable part of our lifestyles. In addition, as human exploration of the Moon's surface and planets other than our own—most notably via the Artemis program—moves forward thanks to international cooperation, we are seeing global expansion in the use of spacecraft, in the form of satellites, space probes, and exploration rovers. With the growing use of spacecraft in this way, there is potential for space system anomalies and the like to develop into major infrastructure failures or even accidents that pose a risk to human life. As such, efforts to ensure even higher standards of reliability and safety are required.

Spacecraft are operated in environments where particles with an electrical charge (charged particles), namely electrons and ions, are present. When spacecraft are exposed to environments containing charged particles, discharging occurs once the amount of charge exceeds a certain threshold. Electromagnetic pulses and the like caused by discharging have the potential to cause the malfunction or failure of spacecraft carrying numerous precision instruments. In 1994, it was reported that the Canadian communications satellites Anik E1 and Anik E2 had actually experienced malfunctions caused by discharging, knocking out television signals and data transmission, with some telephone services cut off for several hours. However, the current situation is that much still remains unclear about the relationship of the space environment to the charging and discharging of spacecraft. To mitigate risks that could impede space exploration and use, and to ensure safety and reliability, measures aimed at warding off fatal breakdowns in operation are required, along with measures implemented at the design stage. To this end, it is vital to learn in advance about the charging of spacecraft by charged particles and their discharging.

We are currently developing a system that uses space weather information to evaluate whether or not the charging and discharging of a spacecraft will occur, in order to ensure spacecraft safety and reliability. Using this charging and discharging evaluation system, it will be possible to avoid anomalies in spacecraft currently in operation, and to develop and select materials that take into account the charging situation of individual spacecraft; this will become a key indicator in spacecraft operation and development. We have also developed an engineering model of an on-board charge measurement device for spacecraft, to ascertain their charging status in actual operating environments (Figure 1).

Measuring charge in actual space environments to ascertain the charging status in real time is expected to lead to greater precision and reliability in the evaluation of charging and discharging, which will make a substantial contribution to identifying and shedding light on the phenomenon of spacecraft charging and discharging. The space environment changes constantly as a result of such factors as operational trajectories and solar activity. As such, the collection of wide-ranging data is necessary in order to improve precision, requiring observation using numerous satellites. As recent years have seen an upsurge in the development of small satellites for coordinated operation in multi-satellite clusters, among others, efforts are underway to develop small multipurpose instruments for installation on small satellites (Figure 2).

We are moving forward with research and development aimed at enabling us to contribute to the stable operation of space infrastructure, whose use is set to expand going forward.

Toward the Creation of the World's First Flare Warning:
Predicting Flares Using a Physics-based Model

BAMBA Yumi

Researcher (Tenure-track), Space Environment Laboratory, Radio Propagation Research Center, Radio Research Institute Ph.D. (Science)

Biography

1988	Born in Gunma Prefecture
2016	Completed doctoral program at Nagoya University Aerospace Project Research Associate, Japan Aerospace Exploration Agency (JAXA)
2019	Designated Assistant Professor (Young Leaders Cultivation Program), Institute for Advanced Research, Nagoya University
2023	Joined NICT's Space Environment Laboratory

Q&As

Q What is good about being a researcher?

A Through my research, I've been able to make friends in other countries. I find it very interesting, because in some areas, we share similar concerns despite being in different countries, whereas in others, we have completely different ways of thinking.

Q What advice would you like to pass on to people aspiring to be researchers?

A You'll have times when you feel you've reached a dead-end with various things—not just in your research. When that happens, don't hesitate to ask those around you for help. You've got more people on your side than you realize.

Q How do you spend your time on holidays?

A Going to a park or shopping with my daughter, and recently we've started cooking together.

When a solar flare occurs, it can cause disruptions in HF communication used in aircraft, as well as interference of signals from the global positioning system (GPS) used in devices like car navigation systems. These effects have already appeared, when a flare is observed from Earth so it is vital to predict the occurrence of solar flares themselves in order to ensure a safe and secure life in our modern society, which relies on advanced information and communication technologies. However, accurate prediction of the location, timing, and magnitude of flares has not yet been achieved globally.

It is known that solar flare is a phenomenon in which magnetic energy accumulated in a solar active region (sunspot region) is explosively released as a result of some trigger. Conventional empirical flare prediction has been based on monitoring the qualitative features, such as the complexity of magnetic field structures in active regions. While this method is effective for predicting relatively small flares that occur frequently, it is not suitable for predicting large-scale flares that are less frequent, but have a greater impact on society. Accordingly, I am developing a system that evaluates and monitors the risk of flares in active regions based on a physics-based model, rather than relying on empirical rules. Following numerical modeling of three-dimensional magnetic field structures in active regions using quasi-real-time data from satellite-based observation of the solar surface, this system carries out fully automated calculation of parameters including the amount of accumulated magnetic energy in active regions, instability, and the amount of releasable energy in those regions. It then visualizes the risk of flare occurrence in each active region.

I have completed development as far as calculating and visualizing these parameters, and have just started using it in space weather forecasting operations. Going forward, I intend to verify the accuracy of large solar flare predictions using this system. I then plan to formulate warning standards based on a user needs survey and consider ways of transmitting these warnings in order to create the world's first flare warning system.

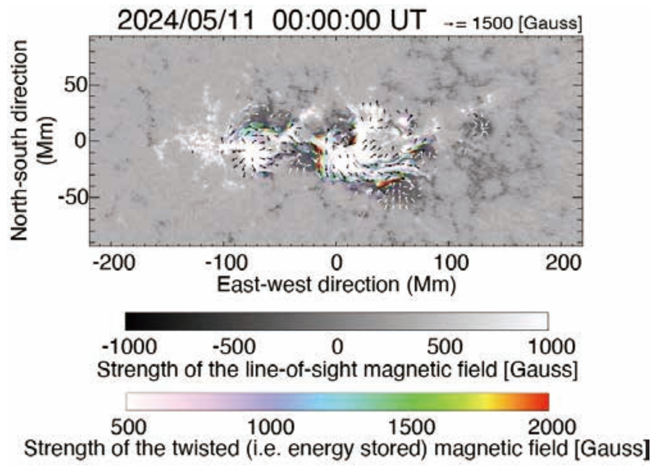


Figure Visualizing the magnetic fields and accumulated energy in an active region. The red areas indicate where a large amount of magnetic energy is accumulated.

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